What Can Be Learned with an Iodine Solar–Neutrino Detector?

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Abstract

We study the potential benefits of an iodine-based solar–neutrino detector for testing hypotheses that involve neutrino oscillations. We argue that such a detector will have a good chance of distinguishing the two allowed regions of Δm^2 – $\sin^2 2\theta$ parameter space if neutrino conversion is occurring in the sun. It should also be able to detect seasonal variations in the signal due to vacuum oscillations and might be sensitive enough to detect day/night variations due to MSW transitions in the earth. Although it would need to be calibrated, a working iodine detector could be completed before more ambitious projects that seek to accomplish the same things.

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Our current understanding of solar neutrinos comes either from water–Cherenkov or radiochemical detectors. Water–Cherenkov detectors have several advantages over their radiochemical counterparts: they are real-time detectors, often with a high count rate, and can provide information on the direction of the incident neutrinos. The existing Cherenkov detectors, however, can measure only the flux of high–energy neutrinos from the decay of ^{8}B. Radiochemical detectors, on the other hand, are unable to determine either the direction of the neutrinos or the exact time of capture, but *can* measure the flux of lower energy neutrinos. Because they rely only on charged-current interactions, they are also better positioned to test neutrino–flavor–oscillation hypotheses; in existing water–Cherenkov detectors neutral current neutrino–electron scattering tends to wash out the variations in signal strength that might result from conversion of solar electron–neutrinos (ν_e) into other neutrino flavors (ν_μ or ν_τ).

It was pointed out some time ago [1] that ^{127}I, operating via the reaction

$$\nu_e + {}^{127}\text{I} \rightarrow \text{e}^- + {}^{127}\text{Xe} \ , \tag{1}$$

would make a useful solar–neutrino detector. The effective threshold for the reaction (1) is 0.789 MeV, low enough to enable the detection of ^{7}Be-, pep-, CNO- and ^{8}B–neutrinos. The cross sections for these neutrinos in iodine were recently computed in Ref. [2]. If that calculation is correct the total event rate in an iodine detector should be 36 SNU, much larger than in chlorine (with the standard–solar–model neutrino fluxes of Bahcall and Pinsonneault [3]). What's more, within the same assumptions, iodine is predicted to be particularly sensitive to ^{7}Be–neutrinos — roughly 14 SNU from that source alone are expected.

Here we show that if these predictions are close to the truth, an iodine detector could play an important role in resolving the solar–neutrino problem. At present, solutions involving purely solar physics are regarded as implausible because they usually require that the flux of ^{8}B–neutrinos be more suppressed more than that of the other solar–neutrino types. The data, by contrast, indicate that the ^{7}Be–neutrino flux is most suppressed [4,5,6,7,8]. The predicted sensitivity of iodine to ^{7}Be–neutrinos makes it particularly suited to test this result. The same prediction also makes iodine useful for testing temporal variations of the signal, due either to MSW oscillations of neutrinos as they pass through the earth (producing a day/night variation [9]) or to vacuum oscillations (producing a seasonal variation associated with changes in the distance between the earth and sun [10]). Other beryllium–sensitive detectors are under development but are years away from actual operation, while a prototype iodine detector should be ready by sometime this summer.

We begin by examining the signal in an ^{127}I detector if the MSW effect [11] — the resonant conversion of solar ν_e's to other neutrino species inside the sun — is the solution to the solar–neutrino problem. Existing experiments have put stringent constraints on the difference Δm^2 between the squares of the masses of the neutrinos and on the mixing–angle θ, the two parameters that determine the transition probability $P(\nu_e \rightarrow \nu_\mu)$. Only two regions in the space of these parameters are still allowed: a small mixing-angle solution with $\Delta m^2 \simeq 6 \times 10^{-6}$ eV^2 and $\sin^2 2\theta \simeq 5 \times 10^{-3}$, and a large mixing–angle solution with $\Delta m^2 \simeq 1.5 \times 10^{-5}$ eV^2 and $\sin^2 2\theta \simeq 0.8$. The quality of the fit in the small mixing–angle region is considerably better than in the large mixing–angle region [12]. The two regions, allowed with 95% confidence, are shaded in all of the graphs in Fig. 1.

To understand the progress that might be made with an iodine detector, we computed expected event rates throughout the two–dimensional parameter space. The corresponding iso–SNU contours, representing curves of constant event rate in the iodine detector, are shown in Fig. 1b, where we have assumed that the neutrino capture cross sections are exactly those calculated in Ref. [2]. With no MSW suppression, the total event rate in iodine is then 36.4 SNU (the contributions of the individual neutrino types are 18.4, 14.0, 1.85, 0.727 and 2.43 SNU for the ^{8}B, ^{7}Be, pep, ^{13}N and ^{15}O neutrinos respectively). The figure shows that in the small mixing–angle region, the total rate is reduced to between 5 and 13 SNU, while in the large–angle region it lies between 10 and 16 SNU . It may therefore be possible to distinguish between the two solutions if the detector clearly registers either less than 10 SNU or more than 13 SNU. The reason for the difference in count rates is that in the small mixing–angle region the ^{7}Be–neutrinos are converted almost completely into other neutrino types, while the flux of the higher–energy neutrinos is reduced only by about 50%. In the large–angle region, by contrast, all fluxes are reduced by 60–70%. The predicted sensitivity to ^{7}Be–neutrinos means that the count rates in the two allowed regions will differ more from one another than they do in existing detectors, which are less sensitive to these neutrinos.

^{127}I is a complicated nucleus, however, and so the cross sections calculated in Ref. [2] carry significant uncertainty. The model used there was designed to represent an entire spectrum of states and the strength to any particular one, e.g. the state accessible to ^{7}Be neutrinos, is highly uncertain. The results of several calculations, within two related but distinct frameworks in Ref. [2] and in an entirely different model in Ref. [13], prompted us to assign a conservative (but tentative) uncertainty of $\pm$ 80% to the ^{7}Be–neutrino cross section. The CNO- and pep- neutrinos can access several low–lying states and so we assigned a nominal uncertainty of $\pm$ 60% for their absorption rate (which is strongly correlated with the ^{7}Be rate). Obtaining an uncertainty for the ^{8}B–neutrino cross section was slightly more complicated. On the one hand, within any particular model, the uncertainty is quite small because of the large number of states involved. Moreover, the results of Ref. [2] are in reasonable agreement with the strength distribution inferred from (p,n) measurements. Unfortunately, the proportionality constant relating the two distributions is at present impossible to determine in odd–A nuclei. Although a sum rule prevents the constant from straying too much, the uncertainty is on the order of 50%, a fact reflected in Ref. [2] by the use of two distinct values for g_A, the effective axial–vector coupling in nuclei. Here we adopted the 50% as a rough measure of the uncertainty in our integrated ^{8}B cross section.

What happens to the iso–SNU curves when the cross sections are varied within the estimated limits? To find out we recalculated event rates for 11 sets of cross sections that differ from those used in Fig. 1b by amounts within the uncertainty ranges just discussed. We assumed that the CNO- and pep–uncertainties are completely correlated with that of ^{7}Be. The results are shown in Table 1 and the corresponding iso–SNU curves for two extreme cases appear in Fig. 1a and Fig. 1c. The table shows that for all the sampled cross section sets there is some chance of distinguishing the small and large mixing–angle regions. Furthermore, the chances are strongly correlated with the ratio of ^{7}Be to ^{8}B cross sections; the higher this ratio, in general, the more likely it is that the count rate will be consistent with one region and inconsistent with the other. Unless the ratio is significantly lower than the value in Ref. [2], an iodine detector could well pin down the mass and mixing angle of

the electron neutrino.

The detector might even be able to test the MSW hypothesis in another way. If the hypothesis is correct, oscillations can occur inside the earth as well as the sun and cause a day/night variation in a detector. For the effect to be measurable the ratio of ^{7}Be to ^{8}B cross sections must be large enough so that variations of the event rate due to oscillations of the ^{7}Be–neutrinos can be observed despite the "background" contribution from boron neutrinos. Our results indicate that if the cross sections are indeed as high as calculated in Ref. [2], this task should be achievable.

We turn now to another scenario; despite all the attention paid to the MSW hypothesis, neutrino oscillations in vacuum remain a possible solution to the solar–neutrino problem, consistent with all existing data [14]. A distinctive feature of vacuum oscillations is a seasonal variation in the event rate due to the eccentricity of the Earth's orbit. The variation is most pronounced for monoenergetic neutrinos. Detectors in which ^{7}Be–neutrinos supply a significant portion of the total signal are therefore better able to test this hypothesis than are water–Cherenkov detectors. Here, as in the case of day/night oscillations, if the value for the ^{7}Be–neutrino cross section is close to the one computed in Ref. [2] an iodine detector would be more useful than any of the existing detectors. In Fig. 2 we have plotted the predicted seasonal variations in iodine, chlorine, and gallium detectors for six pairs of parameters Δm^2 and $\sin^2 2\theta$ that are still allowed by the solar–neutrino data. The normalization R of the signal, described in detail in Ref. [15], is obtained by dividing the signal measured in a particular run by the average observed over one year. Presented in this form the variations of the signal do not depend on the total neutrino flux from the Sun, but only on the parameters Δm^2 and $\sin^2 2\theta$ and on the individual detector characteristics. As is clear from Fig. 2, the amplitude of the seasonal variations in all six cases is considerably larger in the iodine than in the other two detectors.

Before an iodine detector can truly be useful, of course, it will have to be calibrated at least to some degree; the arguments presented here rely on calculations that as we have noted carry considerable uncertainty. Fortunately, a program to directly measure the cross section of neutrinos on ^{127}I at different energies is underway. The program consists of three parts: a measurement of the total cross section for stopped–muon–decay neutrinos at LAMPF, a more direct measurement of the cross section for ^{8}B–neutrinos, and the use of an intense ^{37}Ar source to measure the cross section for ^{7}Be–neutrinos.

The LAMPF measurement (already underway) is intended to determine the sensitivity of an iodine detector to ^{8}B–neutrinos from its response to a beam of neutrinos produced by the decay of stopped muons. Located 7 meters from the proton beam stop and heavily shielded, the detector is filled with 1.5 tons of iodine — 7.5×10^{27} atoms of ^{127}I — in the form of sodium iodide dissolved in water. ^{127}Xe is periodically extracted from the detector; preliminary measurements were recently reported in Ref. [16]. Ref. [2] argues that it will probably be difficult to extract *solar*–neutrino cross sections from this experiment, but that conclusion may change if calculations of forbidden transitions improve in accuracy or if the LAMPF cross section turns out to be smaller than the preliminary result. In any event the analysis is continuing.

More direct measurements of the response of ^{127}I to ^{8}B–neutrinos are possible. The reaction ^{6}Li(^{3}He, n)^{8}B can be used to produce an intense source of ^{8}B; the cross section for the production reaction was measured some time ago by Marrs et al. [17]. Another approach

is to determine the neutrino cross section as a function of energy by measuring the energy of each neutrino from a LAMPF–like source that interacts in a NaI–crystal electronic detector. The secondary–particle interaction signal, coming from the outgoing electron and gammas observed in the NaI crystal, would fix the energy of the incident neutrino. Since the neutrino spectrum from the decay of stopped muons is well known, the corresponding cross section could then be determined. The construction of an appropriate detector is currently under consideration.

The most important quantity for our purposes is clearly the response to ^{7}Be–neutrinos. The ideal calibration source is ^{37}Ar [18], which gives rise to monoenergetic neutrinos of 0.814 MeV. ^{37}Ar can be produced via neutron capture by ^{36}Ar or via the reaction ^{40}Ca(n, α)^{37}Ar. Ref. [19] reports preliminary plans to use the latter reaction to produce a megacurie source of ^{37}Ar. The hope is that this experiment will measure this crucial cross section with a precision of 10%.

A 1/10 scale iodine solar–neutrino detector containing 100 tons of ^{127}I (5×10^{29} atoms) is now under construction at the Homestake Mine. A total interaction rate of 11.5 SNU, the dividing rate between the small and large mixing–angle solutions in Fig. 1, would lead to 0.5 ^{127}Xe atoms per day in the 100 ton detector. With corrections for decay before extraction and for counting efficiency, this gives 120 observed ^{127}Xe decays per year. Even with the prototype detector, a 20% seasonal variation, due either to neutrino oscillations in vacuum or to resonant conversion in the earth, could probably be detected at the 3σ level with two years of data. The full–scale iodine detector could of course do much better.

Several other solar–neutrino detectors are planned for the next few years; two of them — SNO [20] and Superkamiokande [21] — are expected to start taking data in the near future. The Icarus experiment [22], though not yet fully funded, may also soon be on line. But none of these three detectors will be able to see ^{7}Be–neutrinos. Thus while they will help us understand the solar–neutrino deficit, they are unlikely to completely solve the problem. The Borexino experiment [23], on the other hand, is designed precisely to measure the ^{7}Be–neutrino flux, but is still years away from operation; futhermore, problems with background from natural radioactivity have not yet been resolved. Two helium experiments [24,25] have ambitious plans to measure both the pp- and ^{7}Be–neutrinos, but are still in early stages of their development and seem unlikely to be completed before the end of the century. By contrast, a full–scale iodine detector could be running in two or three years. Provided it can indeed be calibrated, an iodine detector therefore offers the best hope for early resolution of the solar–neutrino problem.

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FIGURES

FIG. 1. Iso–SNU contours for an iodine detector superimposed on the regions still allowed with 95% confidence. Labels on the curves are event rates in SNU's. In Fig. 1b it has been assumed that the neutrino–capture cross sections are those calculated in Ref. [2], while in Fig. 1a (Fig. 1c) the integrated cross sections have been assumed to be smaller (larger) by 50% for the ^{8}B–neutrinos, 60% for the CNO–neutrinos and 80% for the ^{7}Be–neutrinos.

FIG. 2. Annual variations R (see text) of the signals in (a) chlorine, (b) iodine, and (c) gallium detectors due to neutrino oscillations in vacuum. The values of the parameters $(\Delta m^2/\text{eV}^2, \sin^2 2\theta)$ corresponding to each curve (all still allowed) are $(5.4 \times 10^{-9}, 1.0)$ — full line; $(1.1 \times 10^{-10}, 0.95)$ — dotted line; $(9.1 \times 10^{-11}, 0.85)$ — short-dashed line; $(8.1 \times 10^{-11}, 0.80)$ — long-dashed line; $(7.8 \times 10^{-11}, 0.80)$ — short-dash-dotted line; $(6.3 \times 10^{-11}, 0.85)$ — long-dash-dotted line.

TABLES

TABLE I. Expected event rates in SNU in the small and large mixing–angle regions for different sets of cross sections (see text). The second and third columns are the ratios of the assumed integrated cross sections for ^{8}B and ^{7}Be to their mean values (from Ref. [2]); they are all within the range of uncertainty discussed in the text. The variation in the cross section of the CNO–neutrinos is assumed to be 100% correlated with that of the ^{7}Be neutrinos.

	^{8}B	^{7}Be	small	large
1	0.5	0.2	2.5 - 5	4 - 5
2	0.5	1.0	3 - 10	8 - 14
3	0.5	1.8	4 - 15	13 - 21
4	1.0	0.2	5 - 11	5 - 8
5	1.0	1.0	5 - 13	10 - 16
6	1.0	1.8	5 - 18	13 - 22
7	1.5	0.2	6 - 15	7 - 11
8	1.5	1.0	7 - 16	12 - 18
9	1.5	1.8	6 - 21	15 - 25
10	0.8	0.7	4.5- 9.5	7 - 11
11	1.2	1.3	6 - 15	13 - 20

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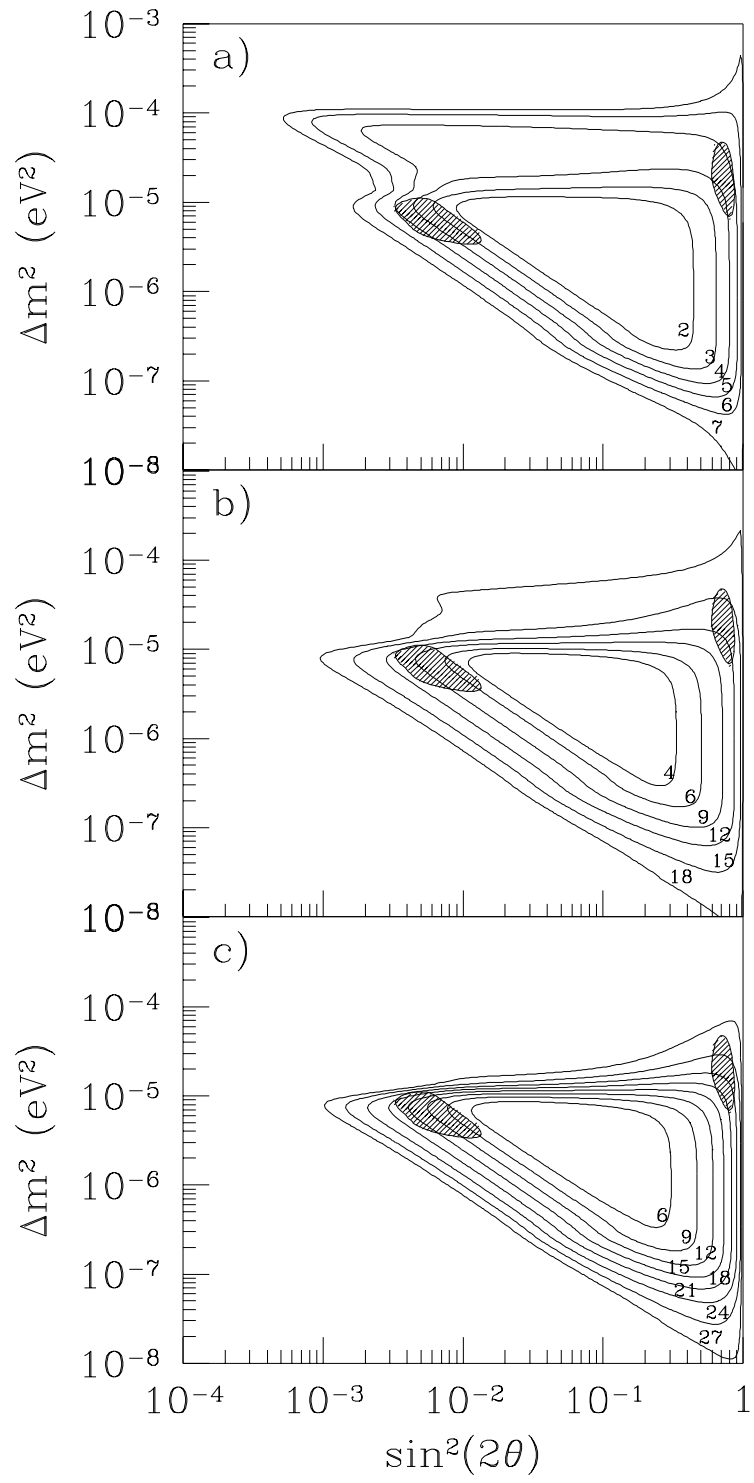
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